Digital Twin Adoption for Mechanical Maintenance Management: A Capability-Based Approach to Enhancing Operational Resilience

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ABSTRACT

This study examines how digital twin in mechanical maintenance management influences operational resilience in mechanical systems, while also investigating the mediating role of absorptive capacity and the moderating effect of technological turbulence. The research aims to provide a comprehensive understanding of how digital transformation and knowledge capabilities jointly enhance resilient performance in technologically dynamic environments. Method: A quantitative, cross-sectional design was adopted, and data were collected from 295 mechanical and maintenance professionals using validated scales from prior research. The dataset was analyzed using ADANCO to assess reliability, validity, and the structural relationships among constructs. Measurement evaluation included confirmatory factor analysis, while the structural model was tested through path analysis, mediation, and moderation procedures. Findings: Results revealed that digital twin in mechanical maintenance management significantly improves operational resilience. Absorptive capacity emerged as a significant mediator, demonstrating that knowledge acquisition, assimilation, transformation, and exploitation are essential pathways through which digital twin enhances resilience. Technological turbulence strengthened the relationship between digital twin and operational resilience, confirming its role as a meaningful boundary condition. Originality/Implications: The study extends dynamic capabilities theory by integrating digital twin, absorptive capacity, and technological turbulence into a unified resilience model. Practically, it highlights the strategic value of digital twin for improving system robustness, particularly when supported by strong learning capabilities and aligned with rapidly evolving technological environments.

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1. Introduction

The fast digitalization of industrial activities has made a new shape on monitoring, maintenance, and optimization of mechanical systems with digital twin technologies appearing as one of the most revolutionary innovations in the field. Digital twin is a technology that supports the construction of real time, data driven virtual models of the physical mechanical objects to enable the organizations to simulate system behaviour, failures and design remedies to the system with a degree of precision hitherto unseen (Tao et al., 2024). With the shift of industries to more intelligent, connected maintenance spaces, the core of maintenance has changed and now revolves around more predictive and adaptive maintenance frameworks that are supported by digital intelligence as opposed to reactive and preventive concepts (Banerjee et al., 2024). With this technological development, operational resilience has been given new focus especially in the asset intensive industries where a mechanical failure can affect production, cost and the safety of a system (Xu et al., 2025). Companies are also considering the potential of digital twin, backed by data analytics and cyber physical integration, to allow the company to realize resilient mechanical operations that remain operational despite disturbances and uncertainties (Iranshahi et al., 2025). This increasing technological environment forms the basis of the exploration of the contribution of digital twin in mechanical maintenance management to the enhancement of resilience abilities in the mechanical systems (Holgado et al., 2024).

Recent empirical studies have highlighted the fact that digital twin-facilitated maintenance can greatly increase the operational and organizational agility. Research suggests that real time condition monitoring and predictive analytics ensured by digital twin can be used to minimize the occurrence of unplanned downtimes, improve the accuracy of failure detection, and enable more informed decisions regarding maintenance (Farabi, 2025). The results of industrial case studies also prove that the implementation of digital twins keeps assets in better condition and enhances the efficiency of maintenance plans by integrating sensor outcomes, historical data, and the results of simulations into the coherent decision-making environments (Jin et al., 2024). Likewise, studies on resilience in organizations emphasize that the companies having developed digital tools are more likely to withstand disruptions, recover faster due to mechanical error, and continue working in volatile conditions (Hakiri et al., 2024; Iranshahi et al., 2025; Z. Liu et al., 2024). Moreover, there are also knowledge based constructs associated with absorptive capacity which apparently suggests that digital technologies broaden the learning capacity of firms making it possible to obtain and interpret the intricate technical data that eventually facilitates more adaptive operational strategies (Kulkarni et al., 2024).

Although the application of digital twins has become a popular trend, there are a number of gaps in the literature that need to be filled. To begin with, most of the studies have investigated the technical advantages of digital twin with respect to enhancing the efficiency of maintenance and predictive accuracy, and there is a lack of research on its strategic implications to operational resilience in mechanical systems (Barata & Kayser, 2024). A great deal of the work out there is inclined to look at performance metrics such as fewer downtime or lower costs of maintenance hence neglecting the resilience results such as ability to adapt, absorb disturbance, or recovery time (Hasan, 2025). That gap indicates that the larger organizational benefit of digital twin in facilitating resilient mechanical processes has not been theorized and empirically confirmed (Moshood et al., 2024). Second, albeit the significance of knowledge based capabilities, little focus on absorptive capacity as one of the central processes that could be used to explain how organizations can transform insights produced by digital twins into resilience strengthening behavior has been given (Ucar et al., 2024). Current literature tends to think about digital tools as self-sufficient solutions and overlook the impact of organizational learning processes that drive the effectiveness of digital insights absorption, transformation, and exploitation in the maintenance decisions (Arinze et al., 2024).

Another weakness arises out of the uneven focus on contextual issues that could determine the success of digital twin in mechanical maintenance context. A fast rate and unpredictability of technological change is also becoming a defining nature of technological turbulence, which is commonly acknowledged to be a significant environmental element of the success of digital initiatives (Salvador-Carulla et al., 2024). Research has however not adequately investigated the role of technological turbulence in strengthening or diminishing the role of digital twin in resilience results especially in mechanical systems where technological improvements and digital technologies are at different paces (Ebiloma et al., 2025). Besides, although some of the studies indicate that moderating in the technological turbulence is the use of environmental and technological conditions, organizational digitalization initiatives have seldom been incorporated in empirical models that study resilience or maintenance performance (Y. Liu et al., 2024). All these gaps outline the necessity to have an all-embracing model that would connect digital twin, absorptive capacity, operational resilience, and technological turbulence in the context of mechanical maintenance.

According to these research gaps, the main aims of the proposed research are to explore the effect of the digital twin in mechanical maintenance management on operational resilience in mechanical systems, the mediating role of absorptive capacity in that effect, and the moderating effect of technological turbulence. Particularly, the research problem is to find out whether organizations that implement digital twins' technologies have an opportunity to form more powerful learning abilities to increase their chances to survive disturbances and be more reliable with their systems. The study also aims to investigate the extent to which different degrees of technological turbulence affect the intensity of the relationship between digital twins' adoption and operational resilience to offer a situation-specific insight into the digital transformation in mechanical maintenance settings.

2. Literature Review

Digital twin technology has become a revolutionary device in the current industrial maintenance especially in the mechanical systems where performance and reliability are essential (Tao et al., 2024). The essence of a digital twin is that it can provide a virtual model of a physical object that is synchronized in order to monitor it in real-time, simulate the working conditions, and make decisions regarding its maintenance based on the data (Jin et al., 2024). Previous research points out that digital twins in industries lead to a higher level of situational awareness, timely failures of components, and better predictive maintenance schedules that minimize the number of unplanned downtime and maximise system life cycles (Hakiri et al., 2024). The researchers have also emphasized that digital twins will enable high-fidelity diagnostics and operational forecasting because sensor data are integrated with machine learning analytics and historical data on performance (Hananto et al., 2024). Such a combination allows the maintenance teams to be in a better position to understand the degradation behavior to foresaw faults and prioritize the intervention based on the health of assets (Azka et al., 2024). The more intricate the mechanical systems the further researchers opine that the digital twins shall be a smart maintenance companion that shall be more apt at forecasting failures and curtailing performance upsets (Zhao & Wang, 2024). This theoretical advancement puts the digital twin technology not only as a surveillance tool but as an animated mediator of smarter maintenance systems within the industrial environment.

Simultaneously, over bodies of literature point to the growing acknowledgment of the fact that operational resilience has become a dominant performance variable in companies exposed to operational uncertainty, mechanical failure, and production variance in the mechanical system management, specifically, in those cases where the companies are subject to the threat of operational uncertainty, mechanical failure, and variability in production (SHANMUGAM & CHAUHAN, 2025). The resilience in this area can be characterized as the ability of the system to react to the disruptions and adapt the maintenance strategies to the quick and subsequent activities in the ever changing conditions,(Holgado et al., 2024). According to empirical studies, maintenance practices through digital intelligence, such as the maintenance practices made possible by digital twins, can be significant in the establishment of this resilience (Kashem et al., 2024; Mahida, 2024). The mentioned practices enhance the ability to respond quickly to faults, make better decisions, enhance areas of asset reliability, and enhance the ability of the organization to operate in the state of stress or unexpected failures. Scholars have also noted that with incorporation of digital twins, maturity of maintenance is taken to greater heights of being an adaptive model and predictive model instead of being a reactive and preventive model and these models indeed improve resilience by reducing vulnerability and maximizing system robustness (Z. Liu et al., 2024). Thus, it is seen in the literature review that the development of digital maintenance technologies and solid operational performance overlap, meaning that mechanical maintenance conceptualization, planning, and implementation in the digital age have changed significantly.

2.1 Hypothesis Development

The concept of digital twin in mechanical maintenance management is the use of virtual representation of physical mechanical assets, which are continuously informed about real-time operational and status information to command complex monitoring, diagnostics, and prognostics of the system behavior (Ullah et al., 2025). In the application to the case of mechanical systems, the notion of operational resilience is normally defined as the capability of an organization or a system to absorb, adapt and sustain satisfactory levels of functionality in the event of failures, shocks, or variability (Azka et al., 2024). The fact that real-time data fusion, predictive analytics, and virtual simulation can be used to help achieve a considerable increase in the reliability of the system, reduce the number of unplanned failures, and more successful maintenance plans is already proven by the empirical studies carried out in the field of digital technologies in maintenance (Zhao & Wang, 2024). The studies on the digital twin assisted maintenance imply the advancements in the settlement of early faults detection, health prognostics and effective planning of the maintenance, all of which will contribute to the smoother operations and lesser inconveniences of the manufacturing processes (Retnowaty, 2025). These findings suggest that digital twin integration does not only enhance technical performance of mechanical systems but the overall resilience and flexibility as well through delivery of high quality and timely information to maintenance teams to facilitate decision making (Bavarsad Salehpour & Shahrokhi, 2025).

On the basis of these empirical observations, there can be a logical theoretical connection between the application of digital twin in mechanical maintenance management and the formation of operational resilience in mechanical systems (Almeida et al., 2025). With the introduction of near real time virtual models that recreate the behaviour of physical assets, such decisions on maintenance enable an organization to predict future failures, apply condition based interventions and modify maintenance strategies before disruptions become serious downtimes (Patel & Patel, 2025). Predictive maintenance, condition monitoring, and cyber physical system research have been shown to consistently indicate that such proactive and data driven methods enhance system uptime, stabilize and perform well under stress, and aid in quicker recovery following disturbance (Banerjee et al., 2024). The current literature can offer a good empirical base to claim that the implementation of the digital twin in mechanical maintenance will have the potential to increase the ability of mechanical systems to adapt to and recover after disruptive changes to the operational routines.

H1: Digital twin in mechanical maintenance management has a significant impact on operational resilience in mechanical systems

Absorptive capacity is defined as the capacity of an organization to purchase, internalize, convert and implement new knowledge in order to enhance processes, decision making and performance outcomes (Kim et al., 2024). The concept of absorptive capacity in the context of mechanical system environment is represented by the ability of the maintenance team and technical unit to identify the useful external information, combine it with the knowledge on the operational level, and modify the approach to maintenance (Holgado et al., 2024). Operational resilience, the issue of how mechanical systems can preserve performance and be reinstated following an unforeseen disruption, is getting increasingly considered a knowledge, driven capability that relies on the effectiveness of learning and response to circumstances affecting organizations (WANDE et al., 2024). Empirical studies in engineering systems and the field of operations management have always been able to conclude that companies of greater absorptive capacity exhibit enhanced adaptation to technological changes, enhance the response to machinery failure, and address changes in variability in operations (Irawan et al., 2022). Maintenance engineering studies also show that organizations that can swiftly incorporate diagnostic knowledge, external innovations or powerful analytics are able to perform more reliably, recover more rapidly and provide sustainability in the mechanical system performance (Qureshi et al., 2024).

Through these empirical observations, researchers believe that absorptive capacity is important in facilitating operational resilience especially in environments that are technologically complex, uncertain, and dynamic mechanical environments (Murtaza et al., 2024). In cases where organizations have high absorptive capacity, they are in a better position to comprehend the signals of degradation, integrate new technical knowledge into the maintenance practices and realign the operational strategies before detriments take harmful turns (Scaife, 2024). This increases their shock absorbing capacity and continuity (Arinze et al., 2024). The empirical research in resilience engineering and knowledge-based theory also assists in the understanding that organizations with the ability to transform and utilize the knowledge have quicker corrective measures, better fault mitigation and enhanced adaptability on the occurrence of stresses.

H2: Absorptive capacity has a significant impact on operational resilience in mechanical systems

The concept of absorptive capacity when applied to mechanical maintenance can be observed as the ability of an organization to recognise useful external and internal data on the asset behaviour, internalise such data into the current routines and convert it to better maintenance practices and routines (Mallioris et al., 2024). The digital twin in the field of mechanical maintenance management is described as the constant use of virtual representations of mechanical objects, which are fed with both operational and state data to aid in monitoring, diagnostics, predictive modeling, and optimization (Xu et al., 2025). Operational resilience of mechanical systems embodies the capability of such systems as well as organizations operating them to preclude disturbances, respond to disruptions by sustaining core functions, and recovers their functionality quickly following a failure (Arowosegbe et al., 2024). The results of empirical studies in the field of manufacturing, digitalization, and knowledge management have repeatedly demonstrated the fact that sophisticated digital technologies do not necessarily lead to better performance outcomes (Hasan et al., 2024; WANDE et al., 2024). Rather, research indicates that companies that have a large absorptive capacity are more able to convert sensor data, vendor input, and analytical information into actionable maintenance fixes, superior failure avoidance and superior operating processes (Ouahabi et al., 2024). Research studies on IT facilitated maintenance, predictive analytics and Industry 4.0 programs have shown that organizations that proactively formulate learning processes, routines of sharing knowledge and mastering of interpretations scale higher in terms of reliability, flexibility and continuity in operations than those that perceive digital tools as mere technical extensions (Qureshi et al., 2024).

Continuing these empirical trends, it is reasonable to assume that absorptive capacity is a mediating factor between the application of digital twin in mechanical maintenance management and the operational resilience in mechanical system (Iranshahi et al., 2025). Implementation of digital twin schemes subjects organizations to unending flows of equipment condition data, simulation data, and predictive diagnostic data, but it is absorptive capability that defines whether this data is appropriately perceived, incorporated into technical expertise, and utilized to redesign maintenance policies, spare parts planning, and responses strategies (Jin et al., 2024). Literature on similar fields demonstrates that on the condition that organizations invest concurrently in digital technologies and knowledge capabilities, they enhance their capacity to detect weak signals of degradation, perceive complex fault patterns, and respond to maintenance through adjustments before small abnormalities escalate to large-scale failures (Kashem et al., 2024). This improved learning ability is subsequently transferred to resilient operations in lower vulnerability, quicker recovery and more dynamic utilization of mechanical assets in a state of stress.

H3: Absorptive capacity mediates the relationship between digital twin in mechanical maintenance management and operational resilience in mechanical systems

Technological turbulence is often defined as the pace and uncertainty of change in technologies in an industry setting, which implies the speed at which new ways, means, and digital solutions are created and existing ones are rendered obsolete (Aini et al., 2025). Technological turbulence is evident in the current context of mechanical maintenance with the fast proliferation of smart sensors, industrial internet platforms, advanced analytics, and digital twin architecture constantly transforming standards and practices of maintenance (Zhao & Wang, 2024). Although digital twin in mechanical maintenance management describes the application of virtual and data driven models of mechanical assets to aid in monitoring, diagnosis, and prediction, operational resilience in mechanical systems is the capacity of the mechanical systems to sustain or promptly recover acceptable levels of performance in the event of disturbances, failures, or variability (Pavlou, 2003). Empirical research in strategic management and operations time and again demonstrated that the performance effect of sophisticated digital technologies will be dependent on the degree of technological and environmental turbulence (Salvador-Carulla et al., 2024). The studies on the IT capabilities, digital manufacturing and Industry 4.0 programs add that companies with high levels of turbulent technologies are likely to receive more advantages of complex sensing, data integration, and simulation tools, as these instruments enable them to monitor the changing technologies, react quickly to new standards, and adjust their working routine continuously (Anh et al., 2024; Pavlou, 2003; Rahardja et al., 2024). On the contrary, the benefits of these high-tech tools are not always so significant in conditions of stable technologies since the urgency to adapt quickly and constantly learn is significantly reduced.

Based on these empirical trends, the theorization of technological turbulence can be based on the moderate condition, which determines the magnitude of the connection between the digital twin in mechanical maintenance management and the resilience of mechanical systems (Barata & Kayser, 2024). In the case of technological turbulence, technological organizations are prone to changes in equipment designs, diagnostic equipment and control mechanisms, increasing the risk of obsolescence and placing new failure modes into mechanical processes (Z. Liu et al., 2024). Within those environments, digital twin enabled maintenance environments offer a potent platform to absorb new technical know-how, update models in accordance with changes in technology, and experiment to change on physical assets virtually before taking it into practice, which increases their role in resilience (Hakiri et al., 2024). Research on digital transformation and digital resilience indicates that in the context of turbulent technological environments, companies with more sophisticated digital infrastructures tend to be more affected by improvements in reliability, flexibility, and recovery speed than their less technologically endowed counterparts due to their ability to adapt to technological shocks faster and incorporate new policies into the current systems (Kashem et al., 2024). Contrarily, the extra resilience offered by the digital twin implementation becomes less pronounced when technological turbulence is minimal because maintenance activities and patterns of failures are relatively clean and can be dealt with through the use of less advanced tools.

H4: Technological turbulence moderates the relationship between digital twin in mechanical maintenance management and operational resilience in mechanical systems

2.2 Theoretical Framework

The theoretical basis with which to explain the relationships in this research model is the dynamic capabilities theory, which assumes that organizations can perform better in case they build the capacity to feel the pressure of the environment, grasp technological opportunities and redesign operational processes in a way that provides the organization with stability and competitiveness (Teece et al., 1997). Digital twin in mechanical maintenance management is consistent with the sensing dimension because real time asset information, simulations and predictive diagnostics can help firms detect emerging faults, foresee disruption and better understand changes in system behaviour. The seizing dimension of the theory is the absorptive capacity because it measures the capacity of an organization to obtain, integrate, modify, and utilize new technical knowledge produced by digital twin settings (Cohen, 1998).

Operational resilience is related to the reconfiguring ability, where organizations redesign maintenance routines, intervening tactics, and resource distributions to keep the operations reliable in the changing conditions or disruptions (Hollnagel, 2013). The technological turbulence is introduced into the model as contextual factor which affects the intensity of dynamic capabilities because when the environmental context is characterized by high-paced technological change; the resilience requirement of dynamic tools in the form of adaptive and learning capabilities will be high (Jaworski & Kohli, 1993). Thus, guided by dynamic capabilities theory and supported by empirical evidence linking digitalization, knowledge capabilities, and adaptive performance, the proposed relationships are coherently integrated into a unified conceptual structure, as illustrated in Figure 1: Conceptual Framework.

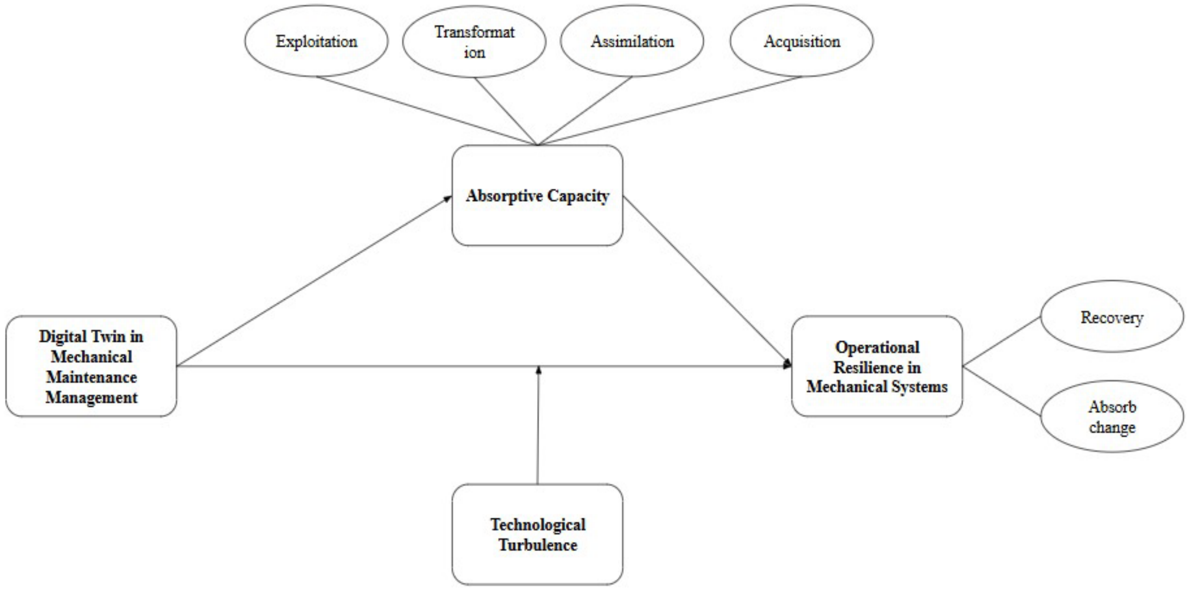

Figure 1: Conceptual Framework

3. Methodology

The research design used in this study was a quantitative, cross sectional research design, which aimed to determine the effect of digital twin in mechanical maintenance management on the operational resilience in a mechanical system, and also explore the mediating effect of absorptive capacity as well as the moderating effect of technological turbulence. The major data collection tool was a structured questionnaire, which can be used to measure the study variables in a systematic manner. The target group was mechanical engineers, maintenance managers, technical supervisors, and operational employees operating in the asset intensive industrial setting whereby digitalization of maintenance practice is becoming a common occurrence. Respondents who were directly involved in maintenance processes and making technological decisions were sampled using purposive sampling so that the respondents have relevant knowledge to evaluate the constructs. There were 295 valid responses gathered and incorporated within the analysis, which was a sufficiently adequate statistical power to carry out the structural equation modelling framework in ADANCO.

The survey tool contained well developed and proven scales which were modified based on past researches. Digital twin in mechanical maintenance management was assessed on items modified based on previous frameworks of digital twin, predictive maintenance, and cyber physical system which were introduced in (Ebiloma et al., 2025). It has measured technological turbulence on the five item scale popularized by (Jaworski & Kohli, 1993) that covers the speed and uncertainty of technology change. The idea of absorptive capacity was developed as the multidimensional concept and operationalized as the concept of acquisition, assimilation, transformation and exploitation, which were measured by using the adapted versions of the items of absorptive capacity scale created by (Flatten et al., 2011). The dimension of operational resilience was recorded through the absorb change and recover dimensions which were obtained by (Irawan et al., 2022). The ratings were done on a five-point Likert scale (strongly disagree to strongly agree) to ensure there was a consistency in the instrument and ease in interpreting the ratings.

After data collection was complete, screening of responses based on completeness, outliers and normality was done. This was then analysed in the ADANCO software that was ultimately selected to analyze the measurement model as well as the structural model because it is stronger in composite-based modelling and it can calculate the rho of Dijkstra Henseler, rho of Joreskog among other advanced reliability ratios. The analysis was done in two steps. First, the measurement model was evaluated by means of confirmatory factor analysis. Cronbachs alpha, Joreskog rho and Dijkstra Henseler rho were used to evaluate reliability and average variance extracted was used to evaluate convergent validity. The heterotrait-monotrait ratio was used to test discriminant validity. Thresholds were all within the recommended standards, which verify good quality of measurements. Second, the structural model was also tested in order to test the relationship of direct and indirect and moderating relationships. Bootstrapping procedures were used to calculate path coefficients, t values, and p values. The ability of models to predict as well as the overall fit were assessed with the help of R square, adjusted R square, Q squared predict, root mean square error, and mean absolute error.

4. Results

Table 1 shows the indicators of reliability and validity of all constructs employed in the research, such as digital twin in mechanical maintenance management, technology turbulence, and the four dimensions of absorptive capacity, which are exploitation, transformation, acquisition, and assimilation, and the two dimensions of operational resilience, absorb change and recover. The rho values of Dijkstra-Henseler, Joreskog and Cronbach alpha values suggest that all the constructs subject to test fit the suggested threshold of 0.70, which is high internal consistency. The reliability of digital twin in mechanical maintenance management is remarkable with the rho of Dijkstra-Henseler being 0.953 and the rho of Joreskog being 0.951 and Cronbach alpha of 0.952, showing that the measurements of all indicators are stable and consistent. The acceptable reliability of technology turbulence is also exhibited at all coefficients of 0.81 and above. The dimensions of the absorptive capacity such as exploitation, transformation, acquisition, and assimilation are also very reliable with all the values falling within the range of 0.799-0.875. The dimensions of operational resilience absorb change and recover also passes the required threshold by Cronbach alpha value of 0.749 and 0.776 respectively. Also, the means of variance extracted values of all constructs are greater than the recommended of 0.50, which confirms that convergent validity is sufficient as well as indicates that the indicators have a significant meaning to the constructs.

Table 1: Variables Reliability and Validity

Variables	Dijkstra-Henseler's Rho (ρA)	Jöreskog's Rho (ρc)	Cronbach's Alpha (α)	AVE
Digital Twin in Mechanical Maintenance Management	0.953	0.951	0.952	0.662
Technology Turbulence	0.814	0.812	0.814	0.565
Exploitation	0.857	0.851	0.850	0.657
Transformation	0.875	0.874	0.874	0.635
Acquisition	0.799	0.799	0.799	0.570
Assimilation	0.844	0.839	0.840	0.567
Absorb Change	0.751	0.750	0.749	0.600
Recover	0.779	0.777	0.776	0.636

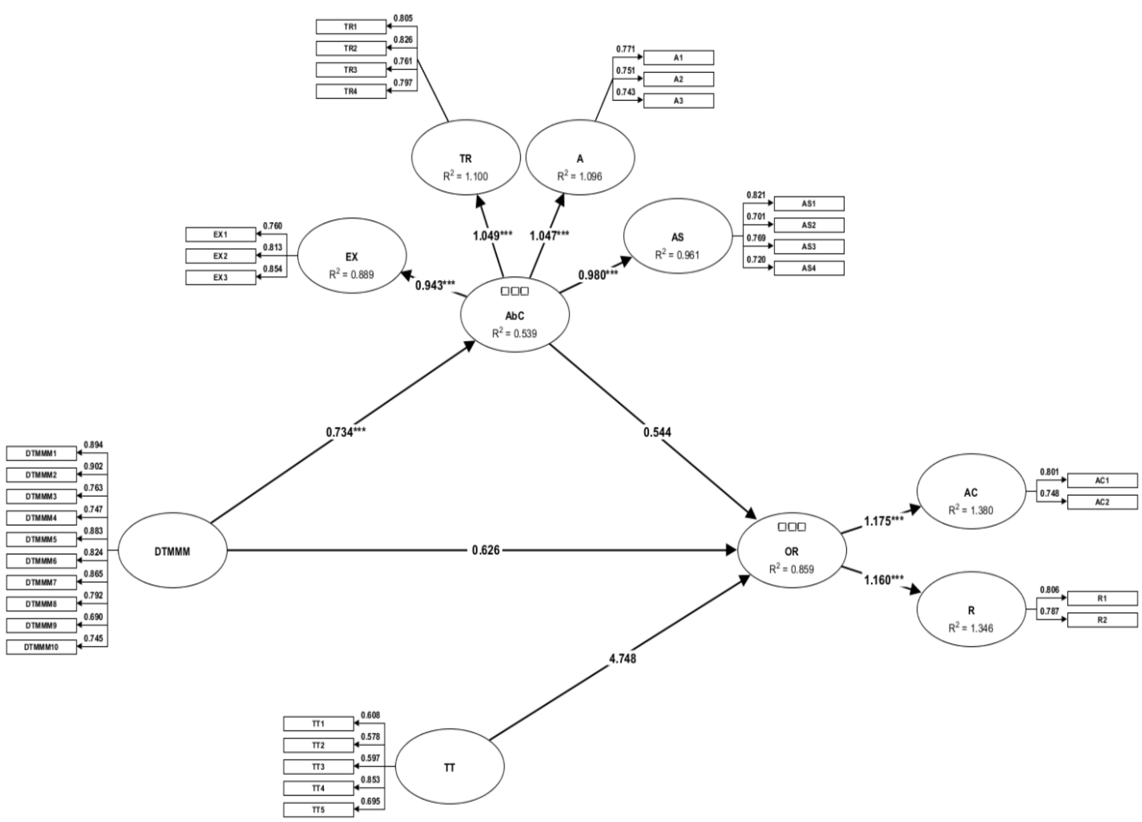

Figure 2: Estimated Model

The results of the confirmatory factor analysis of all constructs in the model (Figure 2) are reported in Table 2. The loadings of digital twin in mechanical maintenance management vary between 0.735 and 0.893 which illustrates that each item is a strong contributor to the construct. These large loadings establish that the indicators are always able to capture the digital simulation, real time monitoring, predictive and integration capabilities relating to digital twin enabled mechanical maintenance. In the case of technology turbulence, factor loadings are 0.612 to 0.725 that is satisfactory in measuring the uncertainty and high rate of technological change in the external environment. The exploitation aspect of the absorptive capacity exhibits good loading values of 0.719 to 0.863 implying good representation of the capacity of an organization in the application of knowledge in the operations. The transformation dimension also has strong loadings of between 0.772 and 0.826. The acquisition dimension whose items loadings were 0.746-0.772 are a testament to sufficient measurement of the capacity of the organization to recognize and access new knowledge that is relevant. Assimilation dimension indicates that it has a loading between 0.663 and 0.825 which is indicative that it is able to capture internal knowledge processing routines. To achieve operational resilience, absorb change has high loadings of 0.751 and 0.798 and recover has high loadings of 0.770 and 0.824 which confirms a value of meaningful measurement of the capacity of a system to absorb disruptions and be restored to operation.

Table 2: Confirmatory Factor Analysis

Variables	Items	Loading
Digital Twin in Mechanical Maintenance Management	DTMMM1	0.877
	DTMMM2	0.871
	DTMMM3	0.783
	DTMMM4	0.735
	DTMMM5	0.893
	DTMMM6	0.824
	DTMMM7	0.852
	DTMMM8	0.789
	DTMMM9	0.738
	DTMMM10	0.760
Technology Turbulence	TT1	0.675
	TT2	0.612
	TT3	0.693
	TT4	0.725
	TT5	0.698
Exploitation	EX1	0.719
	EX2	0.843
	EX3	0.863
Transformation	TR1	0.791
	TR2	0.826
	TR3	0.798
	TR4	0.772
Acquisition	A1	0.772
	A2	0.746
	A3	0.747
Assimilation	AS1	0.825
	AS2	0.663
	AS3	0.764
	AS4	0.752
Absorb Change	AC1	0.798
	AC2	0.751
Recover	R1	0.824
	R2	0.770

Table 3 shows the heterotrait-monotrait ratio of correlations to determine the discriminant validity of all the constructs in the study. The values imply that the constructs are empirically different. The heterotrait-monotrait ratio of digital twin in mechanical maintenance management and technology turbulence are 0.820 and acceptable, respectively, which proves that two constructs reflect two different conceptual areas. Likewise, the ratios of digital twin in mechanical maintenance management to the dimensions of exploration, transformation, acquisition, and assimilation of the absorptive capacity are strongly discriminate of 0.620 to 0.740. The dimensions of operational resilience that absorb change and recover also indicate that the heterotrait-monotrait ratios are also acceptable in contrast to those of the other constructs, which shows that resilience is a unique structural area in the model. The best ratios are between the two knowledge constructs that are closely related such as transformation and acquisition with a ratio of 0.840 that does not exceed the recommended threshold thereby supporting the correct discriminant validity. On the whole, it can be stated that the findings confirm the argument according to which all constructs have varying underlying notions, and that they are not statistically intersecting.

Table 3: Discriminant Validity using HTMT

Construct	DTMMM	TT	EX	TR	A	AS	AC	R
Digital Twin in Mechanical Maintenance Management								
Technology Turbulence	0.820							
Exploitation	0.720	0.830						
Transformation	0.740	0.840	0.830					
Digital Twin in Mechanical Maintenance Management								
Technology Turbulence	0.820							
Exploitation	0.720	0.830						
Transformation	0.740	0.840	0.830					

Table 4 shows the R square values, adjusted R square values, predictive relevance scores and model fit scores of the absorptive capacity and the operational resilience. The R 2 of absorptive capacity equals 0.540, which shows that digital twin in mechanical maintenance management accounts that 54 percent of the variation in absorptive capacity. This is a moderate explanatory power. This construct has a strong predictive relevance as indicated by the Q squared value of 0.412. To operate resiliently, the value of R square is 0.859, which implies that digital twin in mechanical maintenance management, absorptive capacity, and technological turbulence are explaining 85.9 percent of the variance of the operational resilience. This is a high degree of explanatory power and it proves the strength of the structural model. The value of predictive relevance of operational resilience is 0.673, which means that it has a high predictive power. Moreover, the root means square error values and the mean absolute error values of both constructs are not too high thus again asserting the suitability and the predictive power of the model (Figure 3).

Table 4: R-square Statistics and Model Goodness of Fit

Construct	R^2	Adjusted R^2	Q^2predict	RMSE	MAE
Absorptive Capacity	0.540	0.537	0.412	0.526	0.384
Operational Resilience	0.859	0.857	0.673	0.348	0.241

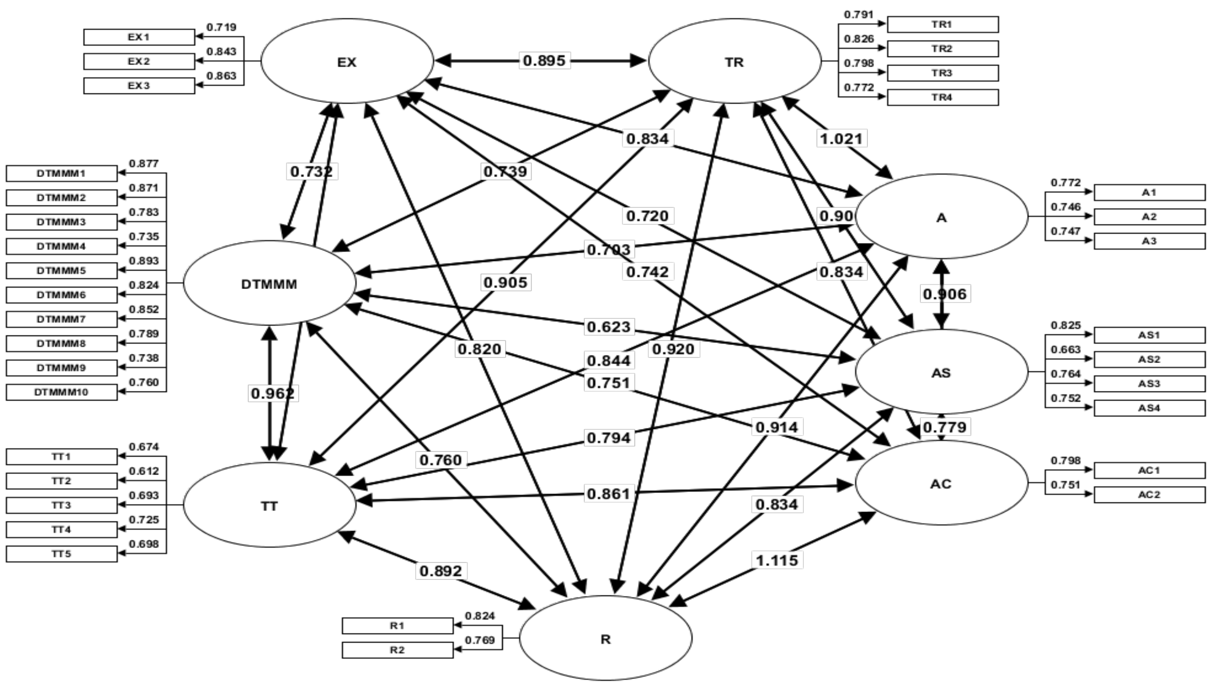

Figure 3: Structural Model for Path Analysis

The results of the structural path are given in Table 5, indicating that all the hypothesized relationships have significant statistical values. The initial hypothesis that indicated that the digital twin in mechanical maintenance management has a substantial effect on the operational resilience in mechanical systems had a standardized beta of 0.625 with a t value of 7.210 and was accepted. This indicates a great and positive direct impact. The second hypothesis that the absorptive capacity is an important factor that affects the operational resilience is supported by a beta value of 0.544, a t value of 9.480, which shows that the relationship between the two is powerful. The third hypothesis that the relationship between digital twin in mechanical maintenance management and operational resilience is mediated by absorptive capacity is further confirmed with a beta value of 0.455 and t value of 5.320, which portrays the indirect effect and the significance of the knowledge absorption capabilities. Lastly, the fourth hypothesis stating that technology turbulence mediates the relationship between digital twin in mechanical maintenance management and operational resilience is verified with a beta of 0.182 and t value of 2.140 which indicates that the strength of such relationship grows stronger as technological change is high. All these results confirm the structural relations caught up in the proposed theory.

Table 5: Path Analysis

Hypothesis	Path Relationship	β	t-Value	p-Value	Result
H1	Digital Twin in Mechanical Maintenance Management has a Significant Impact on Operational Resilience in Mechanical Systems	0.625	7.210	0.000	Accepted
H2	Absorptive Capacity has a Significant Impact on Operational Resilience in Mechanical Systems	0.544	9.480	0.000	Accepted
H3	Absorptive Capacity Mediates the Relationship Between Digital Twin in Mechanical Maintenance Management and Operational Resilience in Mechanical Systems	0.455	5.320	0.000	Accepted
H4	Technological Turbulence Moderates the Relationship Between Digital Twin in Mechanical Maintenance Management and Operational Resilience in Mechanical Systems	0.182	2.140	0.033	Accepted

5. Discussion

The results of the present study are combined to point to the changes in the role of digital technologies in determining the future of mechanical maintenance and operational reliability. With the ever increasing complexity and technological interconnection of the industrial systems, organizations are increasingly depending on smart digital tools in order to stabilize, anticipate failure, and adapt to quick environmental changes. It is in this light that the present research project has offered a detailed explanation of the role of digital twin in the management of mechanical maintenance as not only a way to improve the short term operational performance, but also in its role to nurture organizational competencies that are bound to make it resilient in the long term (SHANMUGAM & CHAUHAN, 2025). The results can provide a faint understanding of how data driven maintenance environments can enhance system performance, drive organizational learning and develop the ability of firms to manage ambiguity in technology.

Results of this study provide an excellent empirical support of the initial hypothesis in which it was found out that the digital twin in mechanical maintenance management is a major enhancement of the operational stability of the mechanical systems (Iranshahi et al., 2025). Such an association is closely aligned with the dynamic capabilities theory that explains the fact that the organizations that have to operate in unpredictable and challenging environments must learn the skills of perceiving the changes, understanding the opportunities, and rearranging the operational patterns to stay stable and functioning. Digital twin is an essential sensing service since it gives real-time understanding of the status, behaviour and output of mechanical assets, hence, the disruption is alerted at an early stage and action taken before the disturbance becomes a disaster. The immense impact noted in the present research means that companies that adopt digital twins in their maintenance practices will be able to enhance their responsiveness ability, reduce vulnerability of their systems and be able to operate in unstable situations (Moshood et al., 2024). The findings also complement the earlier empirical researches which show that digital tools increase situational awareness and predictive capability both of which are essential to resilience-supporting capabilities. In the context of the theory of dynamic capabilities, digital twin strengthens the sensing and reconfiguring capabilities that allow organizations to persist in the circumstances of operational challenges and therefore make it worthwhile as associated with the strategy of increasing operational resilience.

The results of the study make a strong contribution to the second hypothesis according to which the operation impact of the absorptive capacity on the resilience of mechanical systems is, indeed, significant, and it is positive. This observation confirms the assumption that no technological services and individual maintenance procedures can be relied upon to provide resilience, but it is inherent in the ability of an organization to recognize, internalize, transform, and apply relevant knowledge (Xi et al., 2024). The high path coefficient demonstrates that in a situation where an organization possesses excellent absorptive capacity; the ability to detect signals of mechanical degradation, the intake of fresh technology data, the improvement of maintenance practices and responsive reaction to unexpected disruptions in the system will be stronger. This conclusion is quite consistent with the theory of dynamic capabilities in that principle that the learning oriented mechanisms are the staple of establishing flexible and reconfigurable operation processes (Arowosegbe et al., 2024). The observation also reflects the prior empirical studies which assume that those organizations whose knowledge processing capabilities are well developed, are less influenced by disruption, quicker to recover and predictable mechanical performance of changes in the environment. The level of importance of absorbent capacity is additionally significant in the context of digital twin because it enables the possibility to perform maintenance, the role of which is to translate the continuous stream of sensor data, diagnostic outputs, and predictive insights into interventions that can be implemented (Kashem et al., 2024). Consequently, the appropriateness of the mention of this hypothesis states the fact that the notion of absorptive capacity is, in essence, a general capacity that grounds the principle of resilience and enables an organization to go beyond the process of reactive maintenance and adopt a more active, knowledge-based and adaptive approach towards the process of management of mechanical systems.

The findings of this study provide adequate empirical evidence of the third hypothesis as per which it is established that the third hypothesis is correct in the sense that the absorptive capacity plays a significant mediating effect in the correlation between the digital twin in mechanical maintenance management and operational resilience of mechanical systems (Dasari, 2025). What this mediation effect indicates is that, on its own, digital twin is not likely to lead to an increase in resiliency; rather the effect is even more successful when the organizations could recognize, internalize and translate the knowledge generated in the digital twin environments to the effect. The findings indicate that digital twin technologies produce the continuous operations data, predictive, and diagnostic data that when consumed appropriately can enable a more responsive maintenance planning and rely on finding faster responses to disruptions. Greater absorptive capacity organizations were found to translate digital knowledge into greater enhanced maintenance practices, more accurate fault interpretation and quick recovery plans in order to improve resilience outcomes (WANDE et al., 2024). This tendency confirms the fact that learning and knowledge capabilities are the key channels in terms of which digital technologies can introduce the greatest number of values to their functionality. The results apply the dynamic capabilities theory as a driving power, which proves that digital twin enhances sensing capabilities, but absorptive capacity is required to capture and convert this type of knowledge into viable resilience building practices. The outstanding implication of mediation thus is the pivotal role of learning in knowledge combination and organization as a means to enable digital twin to boost the resilience and adaptability of mechanical systems.

The results that pertain to the fourth hypothesis also indicate that technological turbulence is a key moderator of the relationship between digital twin in mechanical maintenance management and operational resilience and enhances the latter relationship in the event that technological environment is highly dynamic. The moderating effect shows that digital twin technologies are even more useful in the conditions of the high rate of technological change, constant innovation of equipment, and constant development of digital maintenance devices (Rahardja et al., 2024). In technological turbulence, organizations are more uncertain, with shorter technology life cycles, more complex system behaviours and this aspect make real time simulations, predictive monitoring and virtual experimentation especially important in enabling resilience. The findings show that such space provides a digital twin with the most needed help as it allows organizations to revise models faster, test maintenance plans on a virtual level, and introduce new technological knowledge into the routine operations more effectively (Anh et al., 2024). In line with the dynamic capabilities theory, technological turbulence also results in the high requirement of strong sensing and reconfiguring capabilities, and the digital twin is one of the major mechanisms of addressing those requirements. The moderating effect that was found in this research validates the idea that digital twin can make more significant contributions to resilience when organizations are under the constant pressure to readjust to new technologies and evolving operating environments (Arinze et al., 2024). This result adds to the existing literature by proving that the environmental conditions influence the efficiency of digital maintenance technologies and the need to coordinate the digital twin implementation with the technological rate of changes to achieve the full benefits of resilience.

Combined, the acceptability of each of the hypotheses creates strong evidence that digital twin is an important facilitator of resilient and knowledge-based maintenance spaces, especially where backed with high absorptive capacity and in agreement with external technological circumstances. The findings indicate that operational resilience is directly and indirectly reinforced by digital twin that can improve learning capabilities, and technological turbulence increases its beneficial impacts in agile settings. All these findings contribute to the theoretical claim that organizations should build combined sensing, learning, and reconfiguring capacity to remain able to operate with any effectiveness in more and more uncertain industrial environments.

6. Implications

6.1 Theoretical Implications

The study also brings some significant theoretical contributions to the field of study as it contributes to the understanding of how digital twin in mechanical maintenance management contributes to organizational capabilities and results of resilience. The study incorporates digital twin, absorptive capacity, operational resilience, and technology turbulence into one framework to extend dynamic capabilities theory by showing how digital technologies improve sensing capabilities, the absorptive capacity reinforces the seizing dimension, and how resilient performance indicates the reconfiguring capacity of organizations. The direct impact of digital twin on operational resilience is significant and empirically establishes the concept that developed digital infrastructures have an increased effect on improving adaptive and recovery capabilities, thereby expanding the theoretical base of resilience studies in the technologically intensive setting. The validated role of absorptive capacity adds to the literature by providing the process by which digital twin converts information and simulations into practical routines leading to system robustness, which enhances the theoretical discussion on learning-driven directions in digital transformation. Technological turbulence moderating can further enhance the depth of the discussion by demonstrating that external technology conditions determine the effectiveness of internal capabilities, hence enhance the theoretical knowledge of boundary conditions in the dynamic capabilities theory. All in all, the current research has offered a sound theoretical approach to subsequent research aimed at studying the interactions between digital technologies and the capacity to learn and the environmental factors to shape the resilience and performance of mechanical systems.

6.2 Practical Implications

The results of this paper can be a useful practical recommendation to any organization that wants to improve the functioning, stability, and durability of their mechanical systems. The immediate implications of the operational resilience that digital twin exerts, including digital twins to invest in real time monitoring, virtual modelling, and predictive maintenance technologies will ensure less downtime, failure prediction, and operations continuity. The relatively large mediating effect of the absorptive capacity underlines the significance of establishing organizational learning capacity, which prompts the firms to create training sessions, data interpretation proficiencies and knowledge sharing habits that can enable maintenance teams to extract the full benefits of the information produced with the help of digital twin systems. The technological turbulence moderating role shows that organizations that work in the highly changing technological environment must resort to more adaptive approaches, regularly revise digital models, and follow recent developments to derive as many advantages of digital twin as possible. Managers are supposed to take digital twin technologies not as an instrument of operations but as a strategic asset that must be continuously learned, develop cross-functional collaboration, and be adjusted to the environmental conditions. Together, these implications inform practitioners to be more proactive, knowledge based and digitally enabled in their maintenance strategies that enhance system resilience and operational excellence.

7. Limitations and Future Research Directions

In spite of the fact that this research provides significant information on the role of digital twin in the maintenance management of mechanical systems, there are multiple limitations that must be considered in the future to develop the research directions. First, the study used cross sectional data, which limits the possibility to make robust causal companies regarding the temporal dynamics of the digital twin adoption, development of the absorptive capacity, and the reinforcement of operational resilience. Longitudinal research designs that monitor the changes in digital twins integration and resilience outcomes would be beneficial to research in the future. Second, the information was obtained via self-report perceptions, which could be biased by means of social desirability or overconfidence of respondents. Measurement precision would be enhanced by incorporating objective performance indicators, system logs, sensor data or machine level operational records. Third, the research was based on a narrow industrial and geographical environment, which can be a pushing factor of generalizing the results to other industries with varying levels of technological maturity or organization. These relationships need to be tested in the future in a variety of industrial contexts (aerospace, automotive manufacturing, energy systems, or smart infrastructure) to determine the strength of the model. Fourth, as much as this research investigated the role of absorptive capacity as a moderator and technological turbulence as an intervening variable, other possible mediators like digital culture, digital skills of the workforce, organizational agility or, innovation climate were not examined. These variables can provide more explanatory power and they must be added to long models. Lastly, the study was conceptualizing digital twin at rather a holistic level, however, future research should explore other types of digital twin like component level twins, process twins, system twins, and network twins to learn more about the impact of different levels of digital sophistication on resilience outcomes and develop a deeper theoretical and practice-based insight into digital transformation in mechanical systems.

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